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ROCK PERFORATION BY PUSED ND:YAG LASER

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Abstract

In gas and oil well completion, perforation channels must be made through the steel casing wall and cement and into the rock formation in the production zone to allow formation fluid to enter the well. This paper will present study results on using a pulsed Nd:YAG laser to drill the perforation channels through reservoir rocks. With fiber optic cable delivery capability, an Nd:YAG laser beam has the potential to be delivered to deep oil production zones. Effects of laser pulse parameters, beam properties, and assistant gas purging on the perforating efficiency and rock permeability will be reported. Unlike the conventional explosive charge perforation that often causes great reduction of rock permeability, laser perforation would enhance the rock permeability, therefore increasing the oil or gas production rate of the well.

Introduction

In gas and oil well completion, perforation channels must be made through the steel casing wall and cement and into the rock formation in the production zone to allow formation fluid to enter the well. Laser/rock interaction test data with the Mid-Infrared Advanced Chemical Laser (MIRACL) and with the Chemical Oxygen Iodine Laser (COIL) show that Berea Grey sandstone permeability in and around the lased area is enhanced due to clay dehydration and microfractures induced by the high temperatures generated in the rock while lasing [1]. Permeability increase of 20-50% for MIRCAL and 20-170% for COIL were reported. This is a significant advantage over the current explosive charges technique that usually produces formation damage or permeability reduction while perforating the rock [2.3] Perforating tests on Berea sandstone with kilowatt level continuous wave CO_2 laser beam showed that clean holes as deep as 5 inches can be efficiently drilled. Drilling a hole deeper than 5 inches became very difficult due to significant tapering of the hole [4]. The data obtained point to the need for improved beam delivery in terms of a collimated beam and gas assist that will protect the optics and remove the rock fragments in the hole efficiently. Perforation operation is conducted in the production zone that is normally thousands-feet deep in the well. This requires the laser beam to be delivered over long distance without great loss of its quality and power. So far, fiber optic beam delivery is the only technology that has the potential and flexibility to deliver the high power beam over long distance with limited power loss. Unfortunately, all three types of lasers mentioned above are currently not able to be delivered efficiently by fiber optic cables. In this paper, perforating test data on Berea sandstone with a high power pulsed Nd:YAG laser beam, which is fiber optic cable deliverable, will be reported. Permeability results of Nd:YAG laser lased rocks will be presented.

Experimental Setup

Laser

The laser used in this study is a 1.6 kW pulsed Nd:YAG laser with fiber optic cable delivery. The specifications of the laser are listed in Table 1: The advantages of pulsed Nd:YAG laser over other types of lasers on rock drilling applications are:

1. It is fiber optic cable deliverable over long distance.

2. It provides dynamic pulsed thermal loading on the rock, which enhances rock spallation.

3. It can be early collimated at a specific spot size. Collimated beam may help reducing hole tapering.

4. It's high peak and low average power provide high power density (W/cm^2) at a given spot size, and yet keep spallation, the most energy efficient rock breaking mechanism, as the dominant rock removal mechanism [5].

Table 1: Specifications of the pulsed Nd:YAG laser

Wavelength	1064 nm
Average Power, P_a	1600Watts
Maximum Energy per millisecond, E	64 Joules
Pulse width, L	0.1 –10 Milliseconds
Repetition rate, R	800 Hz

Perforation Method

A trepanning method was used to perforate the rock as shown in Figure 1. A stationery beam of 12 mm in diameter was offset 6 mm from the rotational center of the rock sample that was mounted on a rotary stage and rotated at a given speed. Nitrogen gas purging of 150 liters/minute was provided by a 1/8" tube that was attached to the laser head and positioned near to the laser beam about 6 mm away from the rotary axis and 5 mm from the sample surface. Laser fired on the rock while it rotating. Between the rotations of the samples, the laser head was adjusted closer to the rock to keep the constant spot size and gas flow at the bottom of the hole as the hole got deeper.

Permeability Measurement

In geology, permeability is a measure of the ability of a rock to transmit fluids. The usual unit for permeability is the darcy or more commonly the mili-darcy or md (1 darcy = 1 x 10^{-12} m^2). The Pressure Decay Profile Permeameter (PDPK) was used to characterize the rocks before and after lasing. The PDPK measures the point permeability at ambient conditions, Klinkenberg slip factor and the non-darcy flow coefficient (Forchheimer). The PDPK has an accuracy of 0.001 md.

Results and Discussions

The process parameters that contribute to the efficiency of rock perforation by a pulsed laser are: laser energy per millisecond, pulse width, pulse repetition rate, beam spot size, beam relaxation time, sample rotating speed, purging gas configuration and gas flow rate. Guideline for parameter selection is selecting the parameters that produce the highest spallation rate or rate of penetration (ROP). Laser parameters at 12 mm diameter spot size were quickly screened by firing the beam at three different parameter settings for 0.5 seconds on a rock sample. Figure 2 shows the shallow spots drilled by the three settings that are E8L1R50 (spot 1), E8L2R50 (spot 2) an E8L2R100 (spot 3). All three settings spalled the rock. But E8L2R100, outputting the highest average power (1600 Watts) and pulse energy (16 J/pulse), was selected for the perforation tests for its fastest ROP.

Table 2. Conditions affected perforation

Rotary Speed (^{0}/s)	**Laser on Time (s)**	**Relaxation Time (s)**	**ROP**	**Sample Cracked ?**
30	12	0	Low	Yes
50	7.2	0	Low	Yes
60	6	0	Low	Yes
60	2	2	High	No

Laser on time, laser relaxation time between laser bursts and sample rotary speed also affect the perforation. A laser burst is the sum of the multiple pulses over the period of laser on time. As shown in table 2, at low rotary speed less than 60 ^{0}/s and/or long laser on time larger than 6 seconds, The ROP was low and sample was cracked (Figure 3 (a)). The cracks acted like an energy absorbing and releasing sources for the input laser energy. As a result, perforation became very difficult. Long laser bursts dumped more energy to the rock than that needed for the local surface spallation, which caused melting and cracking of rock. Pulsing the laser bursts at 2 second on and 2 second off at high rotary speed of 60 ^{0}/s prevented the rock from cracking and the ROP was high (Figure 3 (b)). A hole of 25 mm diameter x100 mm depth was perforated in a 76 mm x 152 mm Berea Grey sandstone core in 80 seconds using the pulsed laser burst methods (Figure 4).

Permeability of pre-and post-lased Berea Grey sandstone by the pulsed Nd:YAG laser are graphed in Figure 5. Data from 16 samples shows that the average permeability is increased from 503 md before lasing to 2847 md after lasing, a 566% increase. The permeability increase is due to clay dehydration and microfractures induced by the high temperatures generated in the rock while lasing. Quartz is a major constituent of the BG sandstone, ~85%. There is a phase transformation at 600 ^{0}C (1112 ^{0} F) for quartz from α- to β-phase which is accompanied by a sudden expansion of the order of 0.8 percent by volume. This sudden volume expansion in the rock during laser beam exposure generates the additional stress built-up in the rock and further enhances the rock permeability and laser spallation rate. Temperature higher than 650 ^{0}C (1200 ^{0}F) was recorded on the tested rock that was fired on by the pulsed Nd:YAG beam at E8L2R100.

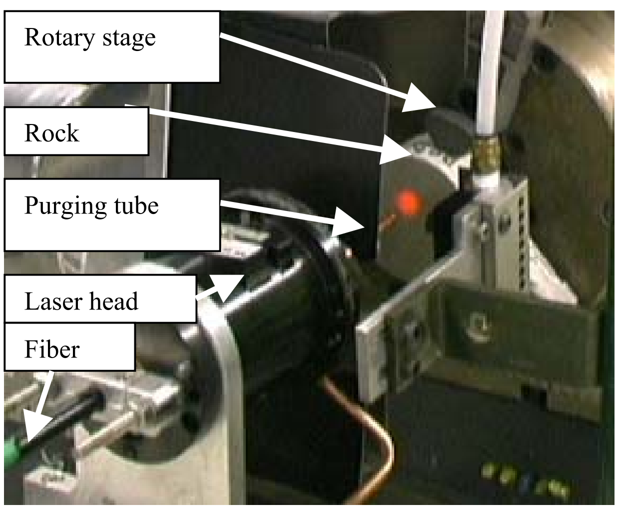

Figure 1. Set up of laser perforation

Summary

Pulsed Nd:YAG laser with fiber optic cable delivery is a strong candidate for laser perforation application for oil and natural gas wells. Preliminary test dada shows that Nd:YAG laser can perforate the rock as efficiently as the other types of high power lasers and the permeability of the rock lased by pulsed Nd:Yag laser beam increases up to 566% compared to non-lased rocks due to clay dehydration and microfractures induced by the high temperature gradient and phase transformation volume expansion generated in the rock while lasing.

Figure 2. Shallow spots drilled by three different laser parameter settings: E8L1R50 (spot 1), E8L2R50 (spot 2) an E8L2R100 (spot 3). The beam size was 12 mm and exposure time was 0.5 second for all three settings.

Reference

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Figure 4. Perforated rock sample.

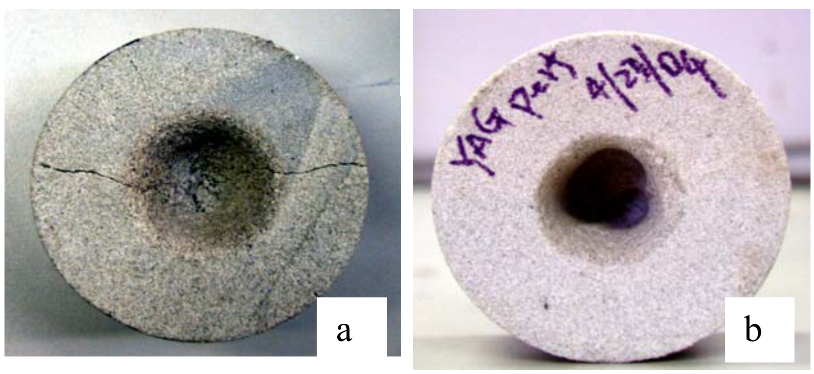

Figure 3. Laser-perforated holes: (a) cracked and (b) non-cracked.

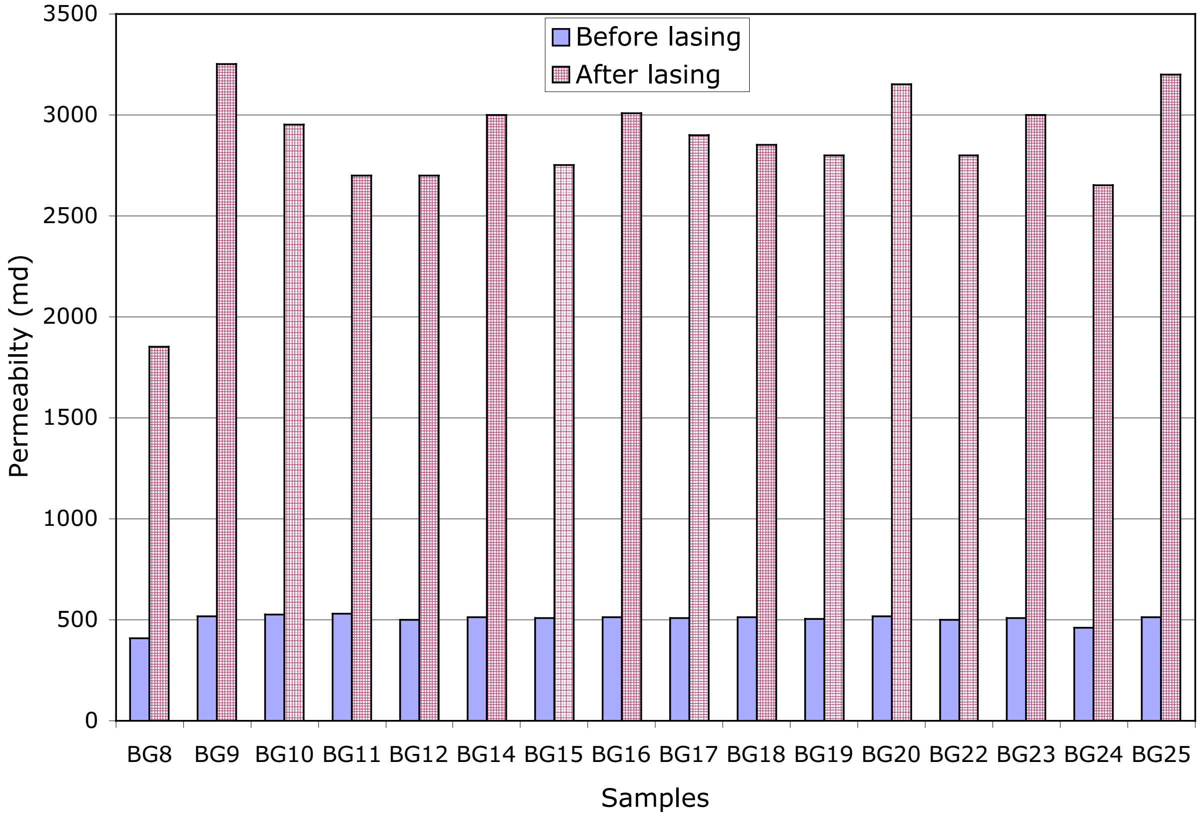

Figure 5. Average permeability of Berea Grey sandstone samples before and after lasing by the pulsed Nd:YAG laser.